SPACE DIVERSITY FOR RECEPTION OF SATELLITE SIGNALS

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ABSTRACT

The use of space diversity for reliability improvement of earth-satellite links operating above 10 GHz is discussed. Diversity gain is defined and the optimum diversity gain is determined. Existing diversity data are used to establish the diversity gain as a function of terminal separation. These data were obtained by Ohio State University in Ohio and Bell Telephone Laboratories in New Jersey at 15 GHz using approximately NW-SE terminal baseline orientations. The data indicate that little improvement is realized for terminal separations exceeding 10 km.

Note: This report is the text of a paper accepted for presentation at the IUCRM Colloquium on the Fine Scale Structure of Precipitation and EM Propagation, Observatoire de Nice, France, 23-31 October 1973.

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I. INTRODUCTION

It has been well established that the reliability of earth-space communication links operating above 10 GHz is significantly reduced by fading due to liquid water in the form of precipitation in the atmosphere. The use of space diversity has been proposed as a means of improving the reliability of such systems as well as that of terrestrial links,[1] and several experiments have confirmed the utility of this approach.[2,3,4] In this paper an attempt will be made to summarize the experimental findings to date in a manner which will be useful to the system design engineer and which will point out the questions remaining to be answered.

The reliability improvement resulting from the use of space diversity is a consequence of the fact that the regions of precipitation producing the fading tend to be finite in both horizontal and vertical extent. Indeed, as the rain rate and associated attenuation rate increase the region of precipitation tends to become more localized.[5] Thus, if two parallel propagation paths are separated spatially the probability of simultaneous fading on the two paths is reduced significantly below the probability of the same fading occurring on a single path. The primary question of interest concerns, then, the degree of reliability improvement resulting from this mode of operation or, alternatively, the extent to which the system margin may be reduced while maintaining a required level of reliability. Coincidentally one must also ask how either of these factors depend upon the spacing of the earth terminals, the orientation of the baseline separating the earth terminals, the number of earth terminals, the frequency of the communication link, the azimuth and elevation angles of the propagation path, and the climatic characteristics of the region in which the earth terminals are located. It is the first three of these factors which will serve as the basis for discussion in the following.

II. DIVERSITY GAIN

The basic quantity which is usually measured in an experiment dealing with this subject is the percentage of time during which a given level of path attenuation is exceeded, i.e., the fade distribution. A hypothetical example of both a single terminal and a diversity fade distribution is shown in Fig. 1 in order to demonstrate the order of magnitude of the depth and percentage time of occurrence of the fading which has been observed. These data represent a composite of the results of several experiments performed in Ohio by Ohio State University and in New Jersey by the Bell Telephone Laboratories.[2,3,4] The system parameters in all cases were approximately the same as the following set of nominal parameters: a frequency of 15 GHz, an azimuth angle of 220°, an elevation angle of 35°, terminal separations from 8 to 34 km., and terminal baseline orientations from NW to SE.

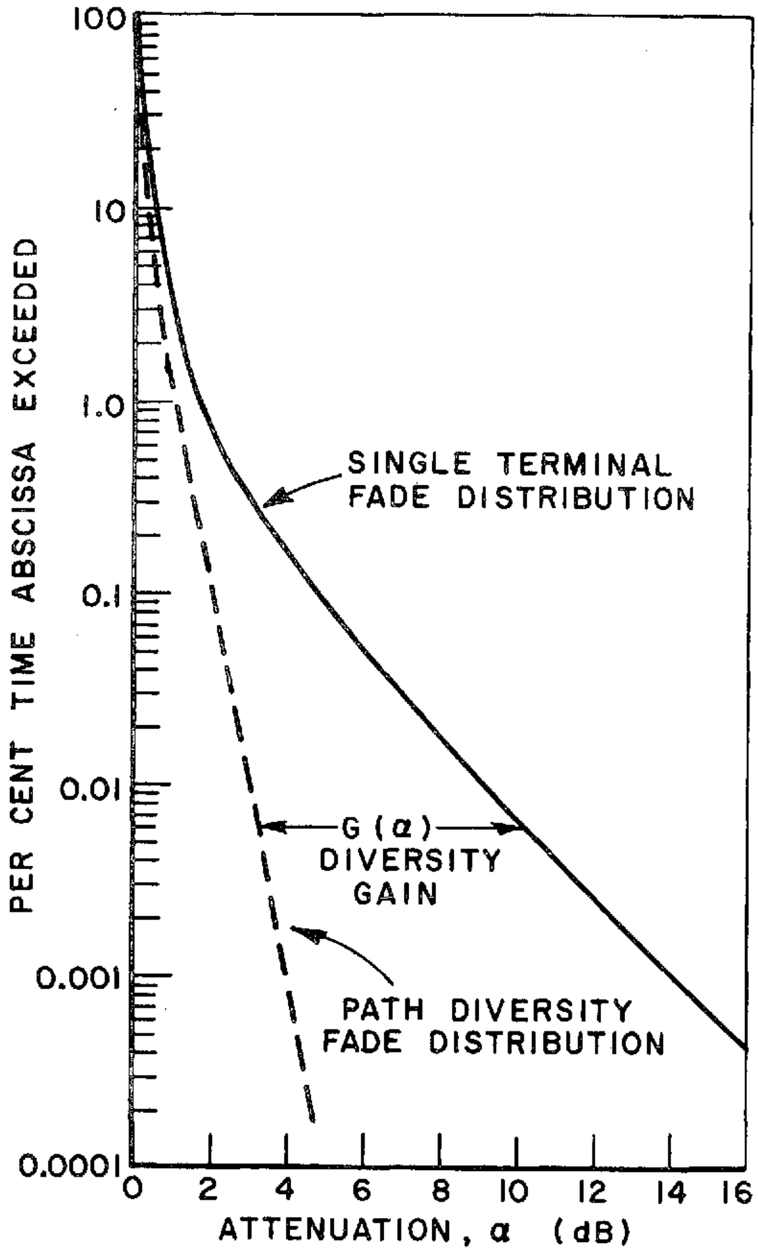

Fig. 1. Typical fade distribution.

Since the data from each individual experiment is in the form of a pair of fade distributions it is difficult to compare the results of one experiment to another directly. Therefore, one may choose to define a parameter such as diversity gain in order to simplify the comparison of experimental results. Diversity gain may be defined as the difference between the path attenuations associated with the single terminal and diversity modes of operation for a given percentage of time, as shown in Fig. 1. Thus, diversity gain is a function of the path attenuation. Further, it has been found that the diversity gain is relatively insensitive to variations in the shape and nature of the single terminal fade distributions found in individual experiments. Finally, since the diversity gain is derived from the fade distributions it is a statistical and not an instantaneous parameter. Physically, diversity gain may be interpreted as the amount by which the system margin may be reduced in the diversity mode to obtain the same reliability as that obtained in the single terminal mode for a given level of attenuation.

Alternatively, one might choose to define as a descriptive diversity parameter the ratio of percentage times of occurrence that a given level of path attenuation is exceeded in the single terminal and diversity modes of operation. If, however, substantial improvements result from the diversity mode of operation, the percentage of time during which a given attenuation level is exceeded may be extremely small and subject to considerable uncertainty. Consequently, the resulting ratio parameter would be subject to the same uncertainty and should be interpreted with care. Therefore, although these two parameters, the difference in path attenuations and the ratio of percentage times, are equivalent in principle, they are subject to different degrees of accuracy in practice.

The optimum, i.e., maximum achievable, diversity gain may be obtained quite simply from a knowledge of only the single terminal fade distribution. Optimum diversity gain will occur when the terminals are located such that the fading at the individual terminals is totally uncorrelated. In this case the probability of the attenuation exceeding a given level simultaneously at both diversity terminals is just the square of the probability of that same event occurring at a single terminal. Hence, the diversity fade distribution and resulting optimum diversity gain can be readily determined from a knowledge of only the single terminal fade distribution. Similarly, the optimum diversity fade distribution for the N-terminal diversity case can be found simply by taking the Nth power of the single terminal attenuation probability distribution function, i.e., fade distribution. These optimum diversity fade distributions are shown in Fig. 2 for the cases of 2, 3, and an infinite number of diversity terminals. These limiting cases have been obtained, of course, for the hypothetical single terminal fade distribution shown; nevertheless, since diversity gain tends to be relatively independent of the shape of the single terminal fade distribution, the optimum diversity gain computed from such an example is quite useful.

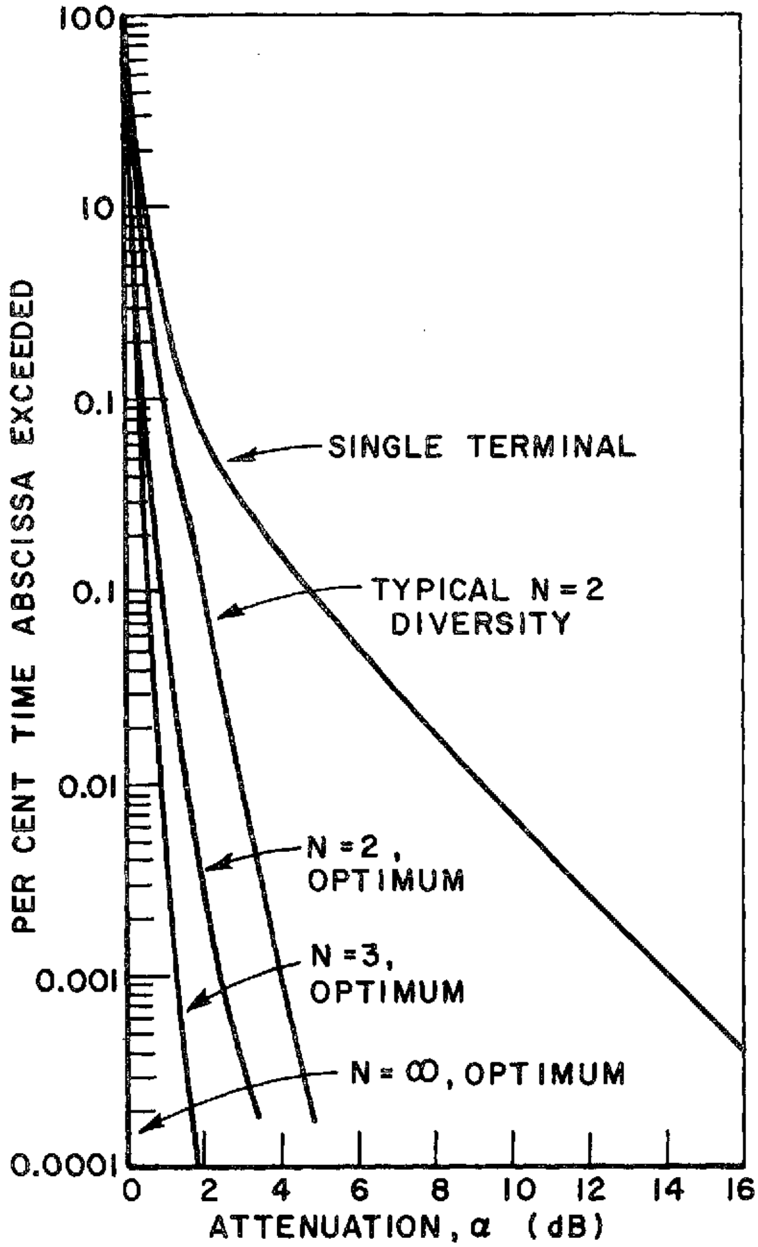

Fig. 2. Optimum diversity gain.

III. TERMINAL SEPARATION

A number of diversity experiments have been performed using either direct attenuation measurements on the ATS-5 satellite 15.3 GHz downlink or attenuations calculated from radiometric measurements. Eight sets of data taken at seven different terminal spacings are available in Refs. 2-4. These experiments all had approximately the same basic set of system parameters as were listed in the preceeding section; the terminals separation distances ranged from 3.2 to 31.4 km. Diversity gain data were extracted from these published fade distributions and are compared as a function of fade depth or attenuation in Fig. 3. It is quite interesting to note that all of the diversity gain data clusters along a band of approximately 1 dB width for separation distances greater than 8 km and fade depths up to 14 dB. This result seems to imply that diversity gain becomes relatively independent of separation distance for distances greater than about 8 km. This implication can be confirmed by considering the optimum two terminal diversity gain taken from Fig. 2; this is shown from comparison in Fig. 4. Here it is apparent that all of the diversity gain data for separation distances of 8 km or more fall within 1.5 dB of the optimum two terminal diversity gain. Of course, in any individual experiment the optimum diversity gain may be computed from the actual single terminal fade distribution without resort to a hypothetical case; similar results are obtained when this procedure is followed for individual cases. It is also interesting to note by comparing the 2 and 3 terminal optimum cases that approximately 1 dB of additional gain may be achieved for the range of fading considered by adding the third terminal.

These results are replotted as a function of terminal separation distance in Fig. 5 to demonstrate the diversity gain trends with respect to separation distance more clearly. Here the independence of the results for separation distances greater than 8 km is quite evident. Furthermore, since the optimum diversity gain result gives an upper bound to this data, we are assured that no substantial increases in diversity gain may be expected even for separation distances exceeding 32 km.

Finally, an additional physical implication may be inferred from the data shown in Fig. 5. First, we observe that the diversity characteristics for separation distances less than 8 km may be modelled quite adequately by a single rain cell model.[6] Second, we note that the diversity behavior for separation distances greater than 8 km is well approximated by the optimum diversity behavior. Thus, it may be inferred that the effect of multiple, closely spaced, i.e., highly correlated, rain cells do not significantly influence the diversity improvement. It must, of course, be emphasized that all of the above conclusions are based upon data from experiments performed in similar climatic regions and with similar system parameters. Variations of diversity performance with other system parameters may not be inferred from the data available.

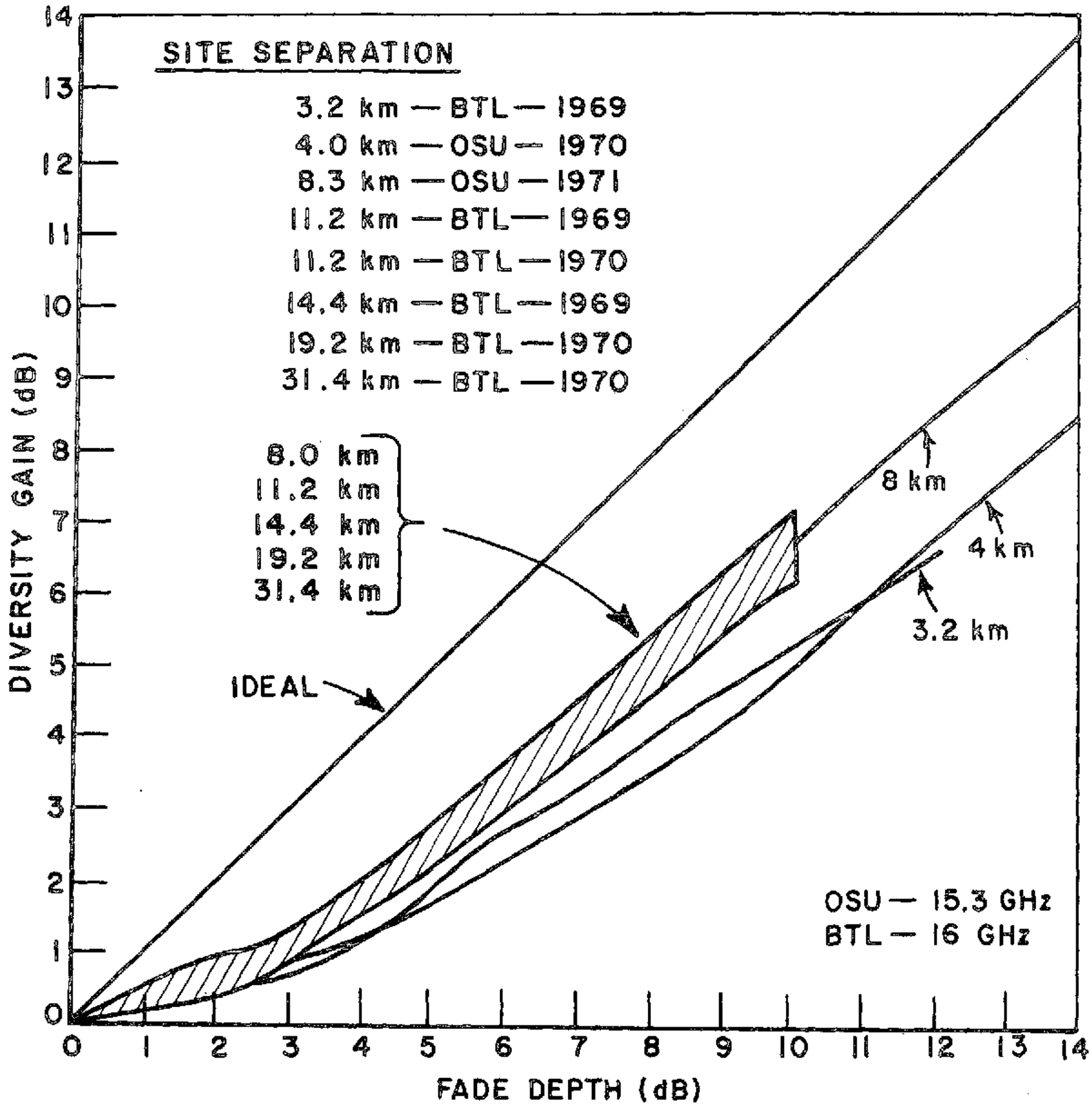

Fig. 3. Diversity gain vs. fade depth.

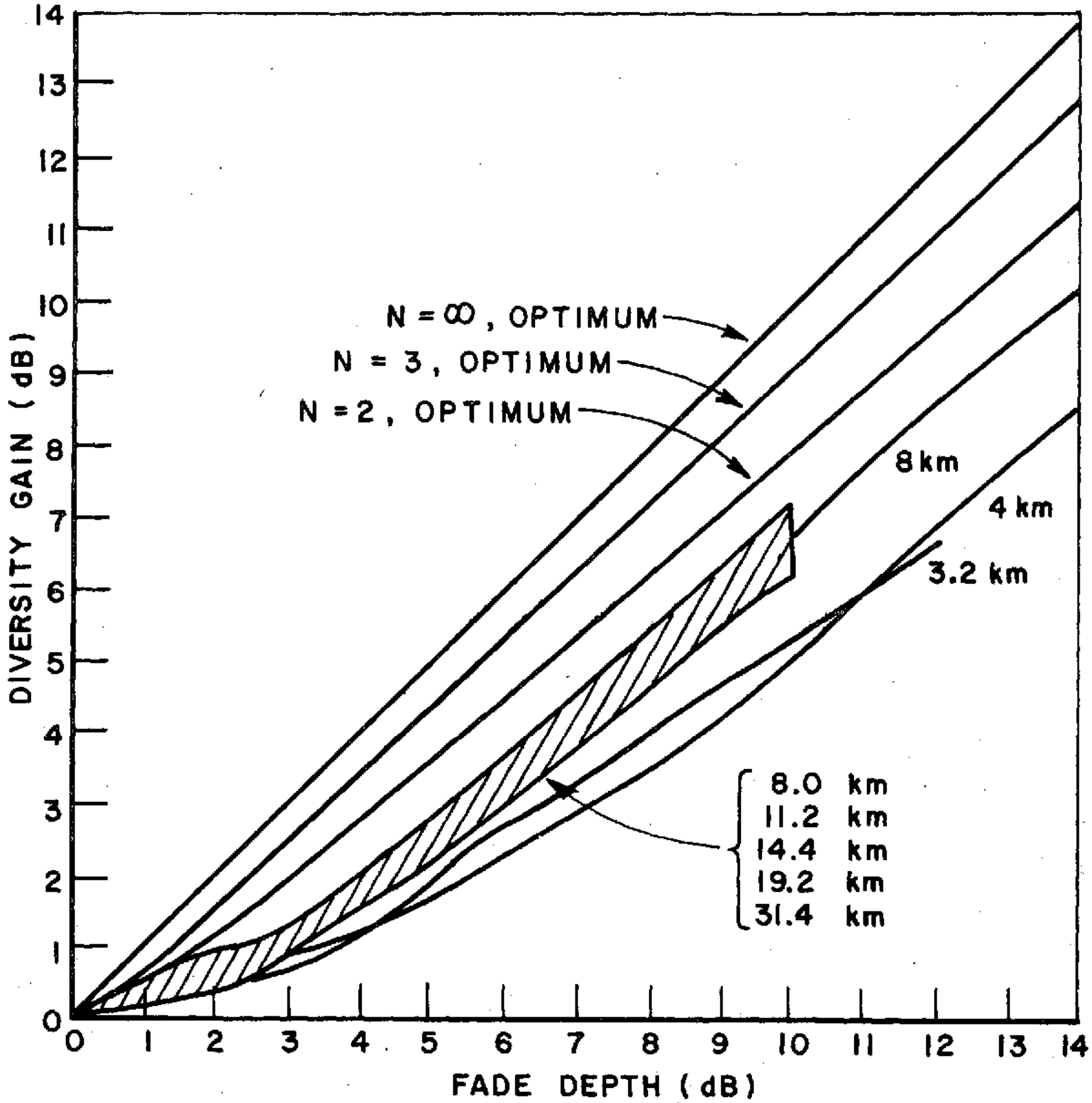

Fig. 4. Diversity gain vs. fade depth.

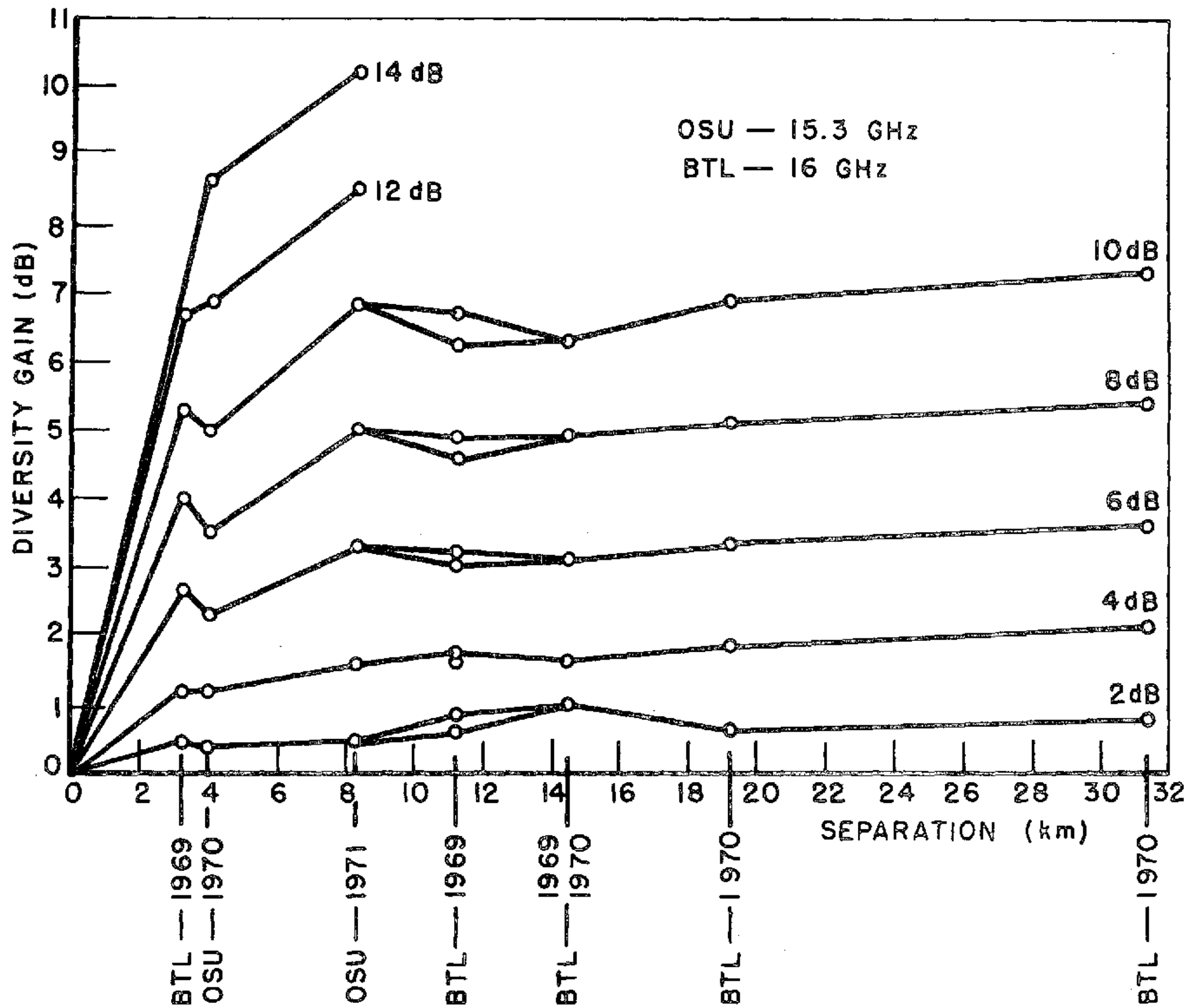

Fig. 5. Diversity gain vs. site separation.

IV. TERMINAL ORIENTATION

The terminal separation data discussed in the previous section were all derived from experiments utilizing terminals oriented along roughly a NW-SE baseline. Consequently, one is led to ask: how does the diversity gain vary with the orientation of the baseline of the terminals. Unfortunately, little experimental data concerning site orientation is available for interpretation. Thus, one must look to physical arguments and theoretical modeling techniques to predict this behavior. The deeper fades encountered at frequencies above 10 GHz may be related directly to the more intense rain rate; and, further, these intense rain rates are often associated with rain cells which are elongated in horizontal extent. Therefore, it may be argued that the rain cell geometry will have a significant impact upon the diversity gain realized with any particular terminal orientation.

In order to examine this characteristic, a theoretical ellipsoidal rain cell model was postulated and utilized to generate fade distributions and diversity gain as a function of both rain cell orientation and terminal orientation. Two of the axes of the ellipsoidal rain cell were taken to be on the earth's surface. The theoretical approach used was similar to that used for the cylindrical cell model in Ref. 6. The geometry is shown in Fig. 6. Without discussing this parametric study in detail, two characteristics consistently observed will be described. First, the maximum diversity gain occurred when the major axis of the rain cell was perpendicular to the terminal baseline. Conversely, the poorest diversity performance was noted when the major axis of the rain cell and the terminal baseline were parallel, i.e., $\psi = \phi$. Thus, if there is a preferred rain cell orientation direction in the region where the diversity terminals are to be located, it is desirable to orient the diversity terminal baseline perpendicular to this preferred rain cell orientation direction.

Shallow fades of only a few decibels are primarily associated with light rain rates extending over widespread regions. Thus, one may conclude that the site orientation will not significantly influence the behavior of the diversity system for shallow fading. However, for deeper fades, e.g., on the order of 10 dB and at a terminal spacing of 10 km the diversity gain may vary as much as 3 dB depending upon the orientation of the baseline relative to the predominant cell orientation. Thus, it is interesting to note that the selection of the terminal baseline orientation may have more impact upon the operation of the diversity system than the addition of a third diversity terminal.

The dependence of diversity performance upon terminal baseline orientation will be one of the experimental objectives in the upcoming ATS-F Millimeter Wave Experiment. Ohio State University is currently instrumenting three 20 and 30 GHz downlink terminals along perpendicular

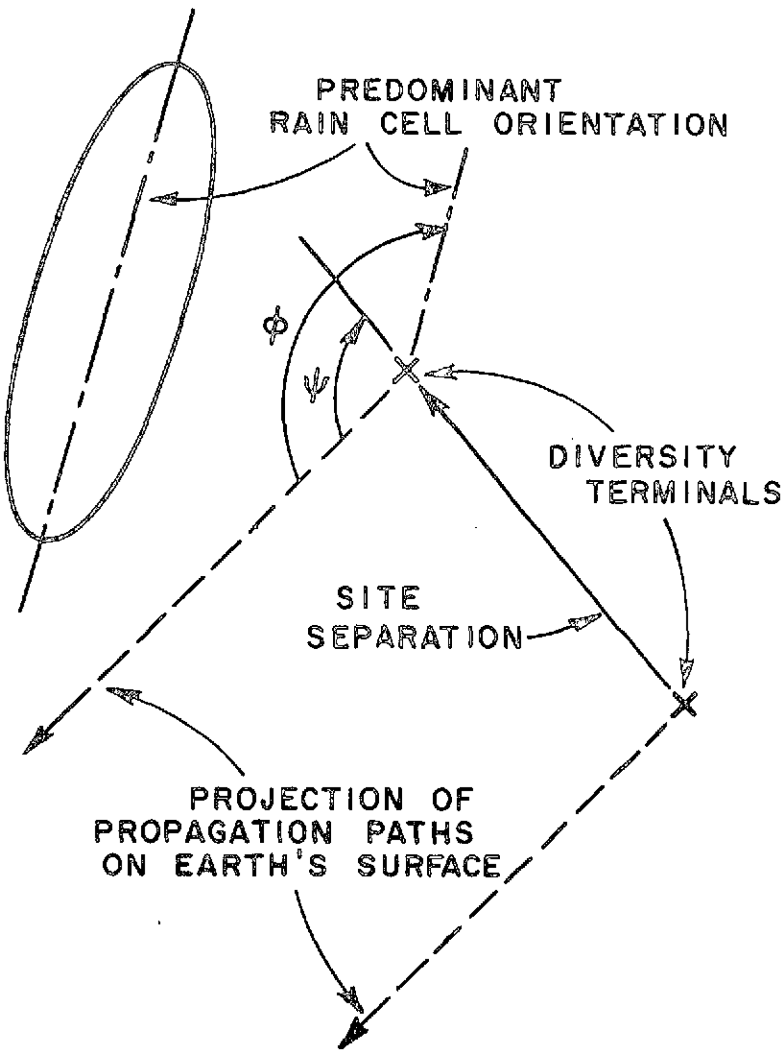

Fig. 6. Site orientation.

baselines for diversity measurements upon the launch of this satellite in early 1974. In a cooperative effort with the Com-Sat Corp., concurrent diversity measurements will be made at 12 GHz. Finally, both the OSU High-Resolution Radar/Radiometer System and the OSU Low-Resolution Radar System will be used to establish the characteristics of the rain cells giving rise to the attenuations observed on the links described above. Thus, it is anticipated that this experiment will shed additional light on the dependence of diversity gain upon terminal baseline orientation as well as terminal spacing, frequency, and rain cell characteristics.

In summary, we see that a substantial amount of information concerning the effect of terminal spacing on diversity gain is available. Current experimental efforts are also being directed toward the question of terminal baseline orientation as well as other factors. Theoretical techniques for the parametric study of diversity gain as a function of terminal spacing, baseline orientation, frequency, look angles, and rain cell characteristics are available and are being pursued. Probably the most severely lacking information is that concerned with instantaneous rain rate distributions, rain cell size and shape characteristics, and the dependence of these parameters on locale.

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